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(54) **Method and apparatus for in-situ and on-line monitoring of a trench formation process.**

(57) With a single wafer dry etching equipment, the trench formation process in a silicon wafer is usually monitored by time-based ellipsometry techniques and destructive SEM cross-section analysis to ex-situ determine trench profile and depth. In particular, the thickness of the SiO_2 layer which is redeposited during the trench formation is monitored by ellipsometry. On the contrary, the apparatus (20) of the present invention allows full in-situ and on-line monitoring of the trench formation process. It is essential that the chamber (22) of the etching equipment be provided with side and top quartz windows. Two spectrometers (30A, 30B) are connected to their respective windows (26A, 26B) by two optical fibers (29A, 29B), so that the optic fibers look at the wafer through the plasma (27) at zero and normal angle of incidence with respect to the wafer plane, respectively. Both spectrometers are tuned to look at the same species radiation, e.g. one SiBr band. Signals outputted by the spectrometers viewing the side and top windows are different:

- side signal Il as a function of time t is representative the band intensity variation during the trench etching;
- top signal It as a function of time t is representative of both the band intensity variation and the wafer surface reflectivity. Thus, signal It is a mixed signal with band intensity and interferometric components.

According to the monitoring method of the present invention the interferometric component signal Ii is extracted by subtracting the side from the top signal. The interferometric signal Ii is of the quasi-periodic damped sine-shaped type. Then, envelope signals Ja and Jb of said interferometric signal Ii, and finally the amplitude variation signal I of the said envelope signals are generated.

The trench depth D is determined in real time by equation:

$$D = k\sqrt{I(t=0) - I}$$

wherein k is a coefficient depending on the etching system that is used and is determined by a preliminary calibration step.

The thickness of the redeposited SiO_2 layer is computed in real time by the equation:

$$Th = \left(\frac{\lambda}{4\ n\ tu}\right) .\ t$$

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wherein λ is the wavelength of the selected species (e.g. SiBr), n is the refractive index of the redeposited SiO_2 layer, and tu is the half-period of the interferometric signal Ii.

D and Th are continuously monitored until the desired final parameters Df and Thf are obtained.

The above method has important applications in the fabrication of deep trenches for DRAM storage capacitors.

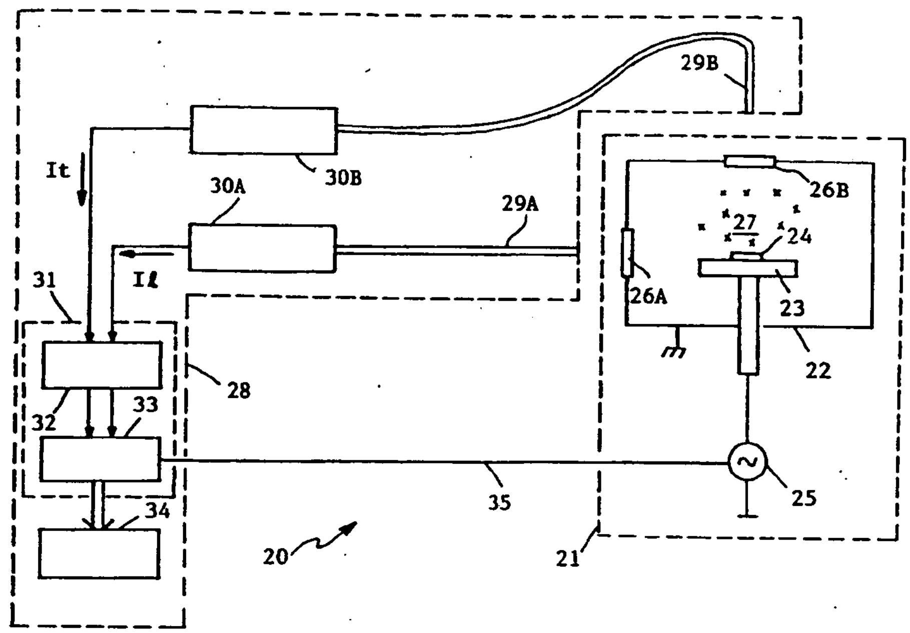

FIG. 6

The present invention relates to integrated circuits incorporating trench structures and more particularly to a method for in-situ and on-line monitoring of the trench formation process by dry etching techniques, which is particularly useful for the etch end-point detection. The present invention also concerns the apparatus for monitoring said trench formation process.

Fabrication of trenches etched in the semiconductor substrate of an integrated circuit which, regardless of their length, have an aspect ratio (depth to width ratio) greater than 1, is desirable in several areas of VLSI processing. In particular, groove-shaped trenches are extensively used as an isolation technique between devices in the semiconductor substrate. Another particular area where trench formation is a critical need is in Dynamic Random Access Memories (DRAMs), where each individual memory cell essentially consists of a MOS transistor/capacitor combination. Higher packing densities may be achieved for MOS DRAMs if the cell area consumed by the standard planar storage capacitor can be decreased. This is achieved by placing the capacitor dielectric on the sidewalls of a hole etched sufficiently deep in the semiconductor substrate to have the equivalent surface area of the planar capacitor. This hole is also commonly referred to as a trench in the literature. Note that trenches in such applications tend to be deeper than those required for isolation purposes, and moreover, have their own specific requirements.

A state of the art trench formation process in the manufacturing of MOS DRAM cells with trench capacitors is given hereafter in conjunction with Figs. 1 to 5, which are cross-sectional views of a semiconductor structure at different steps of the process. As shown in Fig. 1, there is illustrated a portion of a conventional semiconductor structure 10, comprising a silicon (Si) substrate 11 coated with a composite insulating trench hard mask 12. Said mask 12 typically consists of an underlying or bottom 25 nm thick silicon dioxide (SiO_2) layer 13, an intermediate 55 nm thick silicon nitride (Si_3N_4) layer 14 and a top 300 nm pyrolitic silicon dioxide (SiO_2) layer 15. The latter is preferably deposited by a Chemical Vapor Deposition (CVD) technique. A layer 16 of a photoresist material, e.g. AZ1350J supplied by Hoechst, Wiesbaden, Germany, is formed on top of the structure with a thickness of about 800 nm. Semiconductor structure 10 must be understood as a part of a wafer to be processed that includes a great number of chips.

The photoresist layer 16 is exposed through a lithographic mask to UV light, then developed as standard to produce a photoresist mask with the desired pattern of openings. In turn, this pattern of openings is used as in a in-situ mask for etching the underlying trench mask 12 by dry etching. Current VLSI dry etching processes are achieved either by high pressure planar plasma etching or by low pressure reactive ion etching. The etch process is typically dependent upon the generation of reactive species (atoms, radicals, ions) from a gas which are adsorbed by the surface to be etched. A chemical reaction takes place between the surface and these species and the gaseous reaction product is then removed from the surface. Typically, a Magnetically Enhanced Reactive Ion Etching (MERIE) plasma etching system such as the AME precision 5000, supplied by Applied Materials Inc, Santa Clara, California, USA, is appropriately used to etch the hard mask 12 through the photoresist mask 16. Different compositions of gas mixtures, e.g. $CHF_3 + O_2$, may be used. Next, the remaining photoresist layer 16 is removed as standard, for example by ashing in O_2 in the same AME 5000 equipment. At the end of this step, the resulting structure with only one opening referenced 17 in the trench mask 12, is shown in Fig. 2. Opening 17 may be a hole as standard but is not limited to that particular circular shape. For the sake of illustration, assuming opening 17 is circular, its diameter or width at the substrate surface is Ws.

Next, the silicon substrate 11 is etched for trench formation using the trench mask 12 as an in-situ mask. Basically, this is accomplished by a relatively complex process which employs a chemistry that causes continuous SiO_2 redeposition as long as the trench is being etched. For instance, a $HBr + NF_3 + SiF_4 + He + O_2$ gas mixture is appropriate because this composition produces fluorine radicals (F) which etch silicon, and bromine radicals (Br) which combine with the etched silicon to form silicon bromide radicals (SiBr), which in turn, react with the oxygen (O_2) to produce said SiO_2 redeposition. Typical gas flows read as follows: HBr(45sccm), NF_3(7sccm), SiF_4(5sccm) and $He + O_2$(13sccm). A simplified description of such a conventional trench formation process will be now given.

In a preliminary cleaning step, a HBr + NF3 gas is used to remove any native oxide particulates that could have been produced on the exposed silicon surface during the former steps. Particulates, and more generally any contamination, cause micro-masking effects that would be detrimental to the DRAM product reliability. The trench mask 12 remaining thickness is around 300 nm after this preliminary step.

In the next step, the $HBr + NF_3 + SiF_4 + He + O_2$ gas composition and the plasma etching system mentioned above are used to selectively etch silicon with the strong anisotropy that is desired. The following parameters are appropriate to carry out the etching step: Power = 700 W, Freq. = 13.56 MHz, magnetic field B = 55 G and Pressure = 13,3 Pa. As the silicon is etched, successive layers of thin pyrolitic silicon dioxyde, assumed stochiometric (SiO_2), are redeposited onto the structure. SiO_2 redeposition insures adequate slope formation and trench side-wall smoothness. This is apparent from Fig.

3, which illustrates the trench formation process at an intermediate stage. In Fig. 3, the SiO_2 redeposited layer referenced 18 has a thickness represented by Th and the trench is referenced by numeral 19. At this stage of the process, the important trench related parameters are the depth D, the thickness Th of the SiO_2 redeposited layer, and taper angle θ.

At the end of the trench formation process, the resulting structure is shown in Fig. 4. The final SiO_2 redeposited layer and the trench are respectively referenced 18f and 19f. The total thickness Thf of layer 18f is around 150nm and the total duration of the etching process is about 10 min. The total thickness of the remaining insulating layers above substrate 11 is about 450 nm.

Finally, Fig. 5 shows the particular profile of the trench 19f that is finally obtained once all the pyrolitic SiO_2 layers 15 and 18f mentioned above have been removed from the structure. At the top surface of the silicon substrate 11 and at the bottom thereof, the trench widths are respectively Ws and Wb. The final trench depth in the silicon substrate 11 represented by Df and the final taper angle θf of the trench 19f, characterize the final profile of the trench.

Th(Thf), $\theta(\theta f)$ and D (Df) are the key parameters of the trench formation process. There is no doubt that the physical characteristics of the trench must be very carefully controlled to achieve satisfactory results in most applications. This is more particularly true in the DRAM technology where the trench cross-sectional profile illustrated by taper angle θf is of particular concern in all respects. The sidewalls of the trench must be substantially vertical, i.e. forming an angle of about 2 degrees from the vertical. In addition, the interior surface of the trench must be smooth, i.e. without any asperity to ensure the integrity of the very thin SiO_2 layer to be subsequently deposited that will form the capacitor dielectric.

Therefore, what is the aim of all DRAM manufacturers, is to monitor such a process for forming trenches having smooth sidewalls and rounded bottom with a controlled slope and depth. In particular, the trench related parameters must have a predetermined and very accurate value, typically, $\theta f = 2$ degrees (plus or minus 1 degree), and Df = 7,5 microns (plus or minus 1 micron).

To date, the SiO_2 redeposition step is continuously followed by ellipsometry to measure the increase in the thickness Th of layer 18 because there is a relatively good correlation between the thickness evolution, (which depends on the etching duration or time t) and the taper angle θ. Unfortunately, the correlation is relatively poor with respect to the corresponding depth D. For example, trenches may have different final depths Df with the same final taper angle θf. This is why, after the termination of the trench formation process steps, a sample wafer at the stage of the structure of Fig. 5, is sliced to provide a cross-section which, through SEM analysis, permits the exact determination of final depth Df and taper angle θf. Should these values be out of specifications, the whole lot of wafers would be rejected.

In summary, such a trench formation process is conventionally monitored by time through inaccurate ellipsometry based techniques which may require several iterative operations until the desired trench depth is reached. At the end of each of the said operations, SEM cross-section analysis are used to determine the real value of trench parameters: taper angle and depth. Therefore, to date, the state of the art monitoring methods are typically based on ex-situ and off-line techniques. In addition, the known methods are expensive (the cost is one wafer per lot at each of said operations) and also time consuming because of the idle process time while waiting for the SEM cross-section analysis conclusions. As a result, the known monitoring methods of the trench formation process present several distinctive difficulties, at which the present invention is aimed to overcome.

Therefore, it is a primary object of the present invention to provide an in-situ and on-line monitoring method of a trench formation process in a semiconductor substrate by dry etching.

It is another object of the present invention to provide an in-situ and on-line monitoring method of a trench formation process in a semiconductor substrate by dry etching that has either manual or automatic efficient etch end-point detection capabilities.

It is another object of the present invention to provide an in-situ and on-line monitoring method of a trench formation process in a semiconductor substrate by dry etching that is different from the conventional monitoring methods based on ellipsometry techniques and SEM cross-section analysis that are costly and time consuming.

It is still another object of the present invention to provide an apparatus to implement said in-situ and on-line monitoring method of a trench formation process in a semiconductor substrate by dry etching.

According to the present invention, the overall etching system includes a dry etching equipment in which the etch chamber is provided with side and top quartz windows and a monitoring apparatus. According to the present invention said apparatus basically includes two spectrometers connected to these side and top windows by two optical fibers so that the optical fibers "look" the plasma at zero and normal angles of incidence with respect to the wafer plane respectively. The spectrometers are tuned to look at the same species radiation, e.g. one SiBr band. Signals outputted by the spectrometers viewing the side and

top windows are different:

- side signal Il as a function of time t is representative of the band intensity variation during the trench etching;
- top signal It as a function of time t is representative of both the band intensity variation and the wafer surface reflectivity. Thus, signal It is a mixed signal with an interferometric component Ii.

The apparatus further includes means for converting said analog signals Il and It in digital values, digital processing and decision means for processing said values and stop the etching process when appropriate, and optionally plotting means for signal display.

According to the monitoring method of the present invention, the said interferometric component signal Ii is extracted by subtracting the side from the top signal. The interferometric signal Ii is of the quasi-periodic damped type. Then, the envelope signals Ja and Jb of said interferometric signal Ii, and finally, the amplitude variation signal I of the said envelope signals are generated.

The trench depth D is determined in real time by equation:

$$D = k\sqrt{I(t=0) - I}$$

wherein k is a coefficient proper to the etching system and is determined by a preliminary calibration step thereof.

The thickness Th of the redeposited SiO_2 layer is computed in real time by the equation:

$$Th = \left(\frac{\lambda}{4\ n\ tu}\right)\ .\ t$$

wherein λ is the wavelength of the selected species (e.g. SiBr), n is the refractive index of the redeposited SiO_2 layer, and tu is the half-period of the interferometric signal Ii.

D and Th are continuously monitored until the desired final parameters Df and Thf expressed in the specifications are obtained. This, in turn, ensures the desired value of θf is also obtained.

The trench formation process is therefore fully and automatically controlled by the in-situ and on-line monitoring method of the present invention.

The novel features believed to be characteristic of this invention are set forth in the appended claims. The invention itself, however, as well as other objects and advantages thereof, may best be understood by reference to the following detailed description of illustrated preferred embodiments, read in conjunction with the accompanying drawings in which:

Figs. 1 to 5 are partial cross-sectional views of a semi-conductor substrate that schematically illustrate a conventional trench formation process.

Fig. 6 illustrates the schematic of the apparatus of the present invention including top and side spectrometers for monitoring the trench formation process illustrated in conjunction with Figs. 1 to 5.

Figs. 7 and 8 are intensity-time curves that illustrate respectively the side and top signals generated by the side and top spectrometers depicted in Fig. 6.

Fig. 9 is an intensity-time curve that illustrates the signal of the quasi-periodic damped type that is obtained by subtracting said side and top signals. The envelope signals of said signal are also depicted.

Fig. 10 illustrates the excellent correlation between measurements of the final thickness of the re-deposited pyrolitic SiO_2 layer effected by the method of the present invention and by standard ellipsometry, for ten wafers sampled in different lots.

Fig. 11 illustrates the excellent correlation between measurements of the final depth of the trench effected by the method of the present invention and by SEM cross-section analysis, for the same ten wafers.

The present invention relates to integrated circuits incorporating trench structures and more particularly to a method for in-situ and on-line monitoring of the trench formation process by dry etching techniques, particularly useful for the etch end-point detection. The present invention also concerns the apparatus for monitoring said trench formation process.

Now turning to Fig. 6, which shows the etching and monitoring system 20 of the present invention. System 20 first comprises a dry etching equipment 21 which essentially consists of: an etch-treatment chamber 22 enclosing a planar-shaped susceptor 23 that holds the article 24 to be processed, typically a silicon wafer, and a RF power supply source 25. According to the teachings of the present invention, it is essential the etch-treatment chamber 22 be provided with two quartz windows 26A and 26B respectively

located at the lateral (or side) wall and at the top of it. An appropriate equipment is the AME precision 5000 mentioned above, which includes a plurality of single wafer plasma etch reactors. With this type of equipment, susceptor 23 is the cathode and the chamber wall is the other electrode connected to ground. The plasma 27 generated between the two electrodes contains species that are representative of the etching conditions. While etching is performed, the emission from these species changes in intensity as a function of time, material etched and surface modifications.

System 20 further comprises the monitoring apparatus 28 of the present invention. Still according to the present invention, two fiber optic probes 29A and 29B are respectively connected to quartz windows 26A and 26B for short distance transmission of the radiation emitted by the different species that are produced in the chamber 22 during the etching process. Each optic fiber probe must provide a solid angle that allows capture of the light from a relatively large area of the plasma 27. It is highly desirable to have the lateral or side optic fiber probe 29A focussing plasma 27 in the close vicinity of the wafer surface and at a zero angle of incidence with respect to the wafer plane. On the other hand, it is essential that optic fiber probe 29B views the wafer through the plasma at a substantially normal angle of incidence. Optic fiber probes 29A and 29B are respectively connected to spectrometers 30A and 30B. An adequate spectrometer is model SD20 available from the Sofie Inst, Arpajon, France. This model of spectrometer is tunable over a wide-range radiation spectrum and, in the present case, is tuned on the wavelength of one particular SiBr band as it will be explained later on. Each spectrometer comprises a monochromator and a detector (not detailed). The transmitted radiation is received by the motor-driven monochromator which filters out all radiation wavelengths except the one selected radiation to be monitored. The selected radiation is then received by the detector. The detector may be either a low-noise diode detector or preferably a low-noise photomultiplier tube combined with an amplifier. Analog output signals Il and It supplied by the amplifying sections of the side and top spectrometers 30A and 30B respectively, are applied to a processing unit 31, which in a preferred embodiment comprises an A/D converter 32 and a software operated computer 33. A plotter (or a chart recorder unit) 34 (and/or a visual display) is connected to computer 33. Plotter 34 allows the plotting of analog signals that are generated according to the present monitoring method. Computer 33 receives the digital signals that are outputted by the A/D converter 32 for signal processing and print on the plotter 34. Also, computer 33 is able to monitor operation of the etch chamber 22 through control line 35 which drives the RF frequency power supply source 25. This line 35 allows automatical switch-off of the etch-chamber at etch end-point detection, when the desired final trench depth (Df) has been attained.

Note that only one spectrometer could be used as well, should multiplexer means be provided, to process sequentially the information that would be supplied alternately by optic fiber probes 29A and 29B. In addition, use of optic fiber probes 29A and 29B could be no longer required, should the apertures of spectrometers 30A and 30B be directly applied against quartz windows 26A and 26B respectively.

Spectrometers and interferometers have well defined usage in the monitoring of plasma or dry etching equipment. Usually, the spectrometer aperture faces the glow discharge produced by the plasma while the wafer is placed horizontally and at some distance thereof. No interference fringes can be produced in these conditions, the spectrometer detects only a change in light intensity of the selected band. Spectrometer 30A is therefore mounted as standard and generates an output signal Il whose amplitude continuously decreases as far as the trench depth increases. Still usually, the interferometer is placed viewing through the top view window, at normal angle of incidence with respect to the wafer plane. Normality is required, because the plasma inside the etch-treatment chamber 22 produces a glow discharge, i.e. a light source where short wavelengths are available with a large choice, under certain circumstances some bands (lines) can produce interferences. In patent application EP-A-394597 assigned to the same assignee as of the present invention, there is described a monitoring apparatus including a standard spectrometer operating in an interferometric mode. As illustrated in Fig. 4 of the cited application, the current signal outputted by the spectrometer is quite sine-shaped. This patent application is incorporated herein by reference.

According to the present invention, optical fiber 29B is also mounted perpendicularly with respect to the wafer, to see it at a normal angle of incidence through the top quartz window 26B. The glow discharge produced by the plasma is thus observed by an optical spectrometer which is then used as an interferometer as taught in the above patent application. Consequently, there is obtained an interferometric-like effect that produces an alternating current of gradually decreasing amplitude with maxima and minima values of the top signal It produced by the top spectrometer 30B. The periodicity of the top signal It comes from the interferences produced by the redeposited SiO_2 layer growth during the trench formation process.

It is important to have the monochromators of both spectrometers 29A and 29B set to look at the same radiation, i.e. the same band wavelength of a determined species. A few considerations are now given about band wavelength selection. During the trench formation process, the glow discharge spectrum shows many silicon bromine (SiBr) bands over a wide range. As a result, silicon bromine was the selected species and

bands 407nm, 614nm, and 828nm were more particularly studied to determine the most useful among them to carry out the present invention. Even if the band intensity is different, the behavior is the same, because all these bands are appropriate to make interferences. The following table indicates for these SiBr band wavelengths, their relative intensity and amplitude variation, as far as the top signal It is concerned.

TABLE

Wavelength (nm)	Relative intensity (arbitrary units)	Amplitude variation (%)
828	100	6
614	20	10
407	15	20

To obtain more periods of the top signal It during the etching duration (from the structure of Fig. 2 to the structure of Fig. 4), with the maximum amplitude variation, the shortest band wavelength, i.e. 407 nm, was selected as suggested by the above table, because this band has the maximum variation in percent. By using appropriate optic fibers, it should even be possible to select a shortest band wavelength of SiBr or even another species, to obtain a higher number of periods for still more accurate interferometric measurements.

According to the present invention, the method of monitoring the trench formation process in a semiconductor substrate comprises completion of the basic following steps in real time:

1. generating top and side output signals, respectively It and Il, from top and side spectrometers as a function of the etching duration or time t;
2. substracting side signal Il from top signal It to generate the interferometric component signal Ii;
3. elaborating the enveloppe signals Ja and Jb of signal Ii and signal I corresponding to the amplitude variation thereof;
4. computing trench depth D using the said amplitude variation signal I; and,
5. computing the thickness Th of the growing redeposited SiO_2 layer from the said interferometric signal Ii as soon as the first half-period thereof is available.

So that the trench formation process is continuously monitored.

During the etching duration, Il and It signals respectively outputted from side and top spectrometers 30A and 30B are of a different nature and contain useful and distinct information:

- signal Il is the current collected from the side spectrometer 30A and is representative of the band intensity variation during the formation of the trench. Signal Il given in intensity (%) arbitrary units versus the etching duration or time t (in seconds) is illustrated by curve 36 in Fig. 7. As apparent from Fig. 7, from the side window 26A we obtain a current where the intensity is continuously decreasing but not linearly. Signal Il decreases fastly at the beginning of the trench formation process and more slowly at the end. Curve 36 could have provided direct information on trench depth, had it been a straight decreasing line. No interference effect modulates this signal. Signal Il is related in some respect to the trench deepness D. When etching is stopped at time tf, the intensity that can then be measured is therefore related to Df.
- signal It is the current collected from the top spectrometer 30B and appears to be representative of both the band intensity variation (as does signal Il) and the reflectivity of the wafer. The latter corresponds to the reflectivity of mask 12 at the very beginning of the etching process when the structure is at the stage of Fig. 2, and to the reflectivity of layer 18 during the trench formation process (see Fig. 3 structure). The intensity variation of signal It during etching is illustrated by curve 37 in Fig. 8, for the same intensity (%) arbitrary units. Thus, signal It supplied by spectrometer 30B is a mixed signal with band intensity and interferometric components, because it is a function of both the etching of silicon in the trench and the reflectivity of the growing redeposited SiO_2 layer 18. Assuming that both signal components intervene linearly, one can write It = Il + Ii, where Ii is referred to as the interferometric component of signal It. As a result, signal Ii can be simply extracted by substracting Il from It. Signal Ii is therefore related in some respect to the thickness Th of the redeposited SiO_2 layer 18 at time t, because it essentially depends on the wafer reflectivity. When etching is stopped at time tf, the current signal that can then be measured is therefore related to Thf.

Now turning to Fig. 9, where curves 36 and 37 of Figs. 7 and 8 respectively, have been reported, the variation of the interferometric component Ii of signal It as a function of the etching duration t is illustrated by curve 38. These curves are those that can be printed on plotter 34. As apparent from Fig. 9, signal Ii is

of the quasi-periodic damped sine-shaped type. Envelopes of curve 38, referenced 39A and 39B, are also represented in Fig. 9, and corresponds to the so-called envelope signals Ja and Jb of the interferometric signal Ii in real time. Signal I is defined as the amplitude variation of the two envelope signals Ja and Jb. When the process starts at t=0, we have I = Is and when the process ends at t=tf, we have I = Ib. Applicant's inventor has discovered that unexpectedly there is an accurate correlation between the variation in real time of signal I and the trench depth. As a matter of fact, said envelope amplitude variations Is and Ib, of the interferometric signal Ii shown in Fig. 9, are respectively representative of the trench widths Ws (at the surface when t=0) and Wb (at the bottom at time t=tf) as defined in the structure of Fig. 5, for all the trenches that are seen by the top optical fiber probe. The thickness Th computation in real time requires the half-period of signal Ii.

All basic signal processing operations including the signal subtraction Ii=(It-Il) in real time mentioned above, can be effected manually by an operator or preferably, automatically by the software operated computer 33. The software is able to separate the mixed information to isolate the interferometric component signal Ii for further processing to extract useful information thereto, as the generation of the envelope signals Ja and Jb and the amplitude variation signal I thereof, as well as to proceed to the different formula computation, as it will be detailed hereafter with respect to the completion of the trench formation process.

Assuming we are in an automatic process, the software is able to calculate in real time the depth D expressed by the square root of the intensity difference between Is and I, i.e. $D = k\sqrt{Is - I}$, wherein Is is the amplitude variation of signal I at time t=0 when process starts. Coefficient k is proper to the characteristics of the etching system 20 and is determined by a preliminary calibration step through SEM cross section analysis.

Simultaneously it also calculates in real time the quasi half-period tu of the interferometric signal Ii as soon it becomes available (about after 400 sec see Fig. 9), and then to monitor the thickness Th of the redeposited SiO_2 layer as a function of time t by the following equation:

$$Th = \left(\frac{\lambda}{4\ n\ tu}\right) t$$

wherein

λ = Wavelength of the selected band (e.g. 407 nm SiBr)
n = Refractive index of SiO_2 layer 18 (n = 1,46)
tu = Half-period of signal Ii
t = Etch time

When D = Df (the desired trench depth) at time t=tf, the etch process is stopped ; tf is therefore the run duration, i.e. time to reach etch end-point or the total etch time.

The results that are obtained with the method and apparatus of the present invention can be compared with those obtained with the conventional ellipsometry and SEM cross-section analysis techniques.

Now turning to Fig. 10, the final thickness Thf of sample wafers selected in ten different lots, referenced X1 to X10, were measured according to the method of the present invention, and then through the standard ellipsometry technique. Values are around the nominal final thickness (Thf)m of about 150 nm, given by the specifications. Curves 40 and 41 respectively join the values found with the monitoring method of the present invention and by ellipsometry. Fig. 10 demonstrates the excellent correlation between the results obtained by the two methods in that respect.

Fig. 11 shows similar measurements with respect to Df, around a nominal trench depth value of (Df)m = 7,5 microns given by the specifications for the same wafers X1 to X10. The final depths of the trenches were first measured according to the method of the present invention, then through destructive SEM cross-section analysis. Curves 42 and 43 respectively join the values found with the method of the present invention and by the SEM cross-sections analysis. There is still an excellent correlation between the results obtained by the two methods in that respect.

Finally, the comparison between the theoretical curves and the measured data is quite satisfactory.

Example

Fig. 9 shows the results that were obtained in one practical experimentation. For the etching system 20 in question, the coefficient k was found equal to about 2,2. Coefficient is generally determined on a monthly

basis, or after occurence of a significant change in the process parameters, by a calibration step on a sample wafer using the monitoring method of the present invention and comparing with a SEM cross-section analysis.

The amplitude variation I was continuously monitored through $I = Is-(D/k)^2$ with $Is = 22$ arb. units.

The desired final trench depth Df is 7,5 μm, so that the final amplitude variation $I = Ib$ is given by :

$Ib = 22 - (7{,}5/2{,}2)^2 = 22 - 11.6$ i.e about 10 arb. units

When this value was attained, the etch process was stopped.

This value Ib determines the total etch time tf, which may be numerically determined from Fig. 9, i.e. tf = 660 s (11 min.).

Simultaneously, the thickness of the redeposited SiO_2 layer 18 was also monitored. The half-period tu is given by Fig. 9, tu = 250 s. At the end of the etching, the final thickness Thf was determined by :

$$Thf = \left(\frac{\lambda}{4\ n\ tu}\right) .tf = \frac{40710^{-9} \times 660}{4 \times 1{,}46 \times 250} = 184\ nm$$

instead of 150 nm, the nominal expected value. Experiments have shown that a Thf value between 100nm and 200nm is acceptable. Outside this range, it is recommended to adapt the gas flow ratios to correct.

Continuous monitoring of Th is important, because if the etching process is going too fast, the redeposited SiO_2 layer 18 (see Fig. 3) grows with an insufficient rate. As a result, the taper angle may be equal to zero (vertical trench sidewalls) or even become negative (the top of the trench exhibits a significant overhang). On the contrary, if the etching process is too low, the redeposited SiO_2 layer grows at a higher rate than desired, and the taper angle will be too important and will not meet the specifications. In both cases, as mentioned above, the gas flow ratios are modified to correct the trench formation process for the next wafer to be processed.

In summary, the interferometric signal Ii allows computation of the thickness of the SiO_2 layer that is redeposited during the trench formation process. The half-period tu is computed as soon as it is available. The selected wavelength and the refractive index of layer 18 are data stored in the computer 33. Thickness Th is therefore easy to calculate in real time. Computation in real time of the trench depth D is also easy once the amplitude variation of envelope signals Ja and Jb of interferometric signal Ii is determined. The initial amplitude variation Is is determined when the process starts and is then stored in the computer.

The numerical example given above broadly corresponds to wafer referenced X8 in Figs. 10 and 11.

To conclude, the monitoring method of present invention when combined with a plasma or dry etching trench formation process safely provides deep trenches that can be reproducibly etched with excellent control of geometries. In particular, it provides trenches having controllable and reproducible characteristics: accurate depth Df and final taper angle θf because θf can be relatively well monitored through the monitoring of parameters Df and Thf.

As a result, DRAM cells having reliable capacitors formed in trenches of about 7,5 microns (or more) depth can be manufactured according the present method of monitoring. In addition, the present method saves time and product wafers at the cost of minimal or even no modification either on the etching equipment or on the optical spectrometers. All hardware parts shown in Fig. 6 can be easily acquired on the market. An easy to design software combined with a personal computer allows on-line and in-situ data acquisition, either simultaneous or sequential (in case only one spectrometer is used), the digital processing of the analog signals supplied by the two spectrometers and, finally real time calculation of the key parameters of the trench formation process by dry etching for accurate monitoring thereof.

Claims

1. An etching system with etch end-point detection capabilities for monitoring a trench formation process in a semiconductor wafer including:

a dry etching equipment (21) comprising an etch-treatment chamber (22) provided with two quartz windows (26A; 26B) in which the semiconductor wafer (24) to be processed is received;

a radio frequency power supply source (25) generating a plasma (27) inside this etch-treatment chamber;

wherein the first window (26A), so-called side window, views the plasma at the close vicinity of the wafer disposed horizontally and the second window (26B), so-called top window, views the plasma and the wafer at a normal angle of incidence; and

a monitoring apparatus (28);

said monitoring apparatus being characterized by:

spectrometer means (30A; 30B) connected to said first and second windows supplying respective side and top output signals (Il; It);

processing and decision means (31) adapted to receive said side and top signals and process them to permanently elaborate in real time the key parameters of said trench formation process and the thickness Th.

2. The etching system of claim 1 wherein said processing and decision means (31) further includes:

means for providing a control signal upon achievement of etch-end point, when the desired final values of said key parameters have been obtained.

3. The system of claim 2 wherein said processing and decision means (31) further includes means (35) for automatically stopping the trench formation process when the said desired final values have been obtained, by switching-off the power supply (25) of said etch treatment chamber (22).

4. The system of claim 1, 2 or 3 wherein said spectrometer means comprises side and top spectrometers (30A, 30B) respectively viewing the plasma through said first and second windows.

5. The system of claim 4 wherein said spectrometer means further includes:

a first optical fiber probe (29A) connected between said first or side window (26A) and said side spectrometer (30A);

a second optical fiber probe (29B) connected between said second or top window (26B) and said top spectrometer (30B);

6. The system of any claim 1 to 5 wherein said spectrometer means are tuned on the same radiation of a same specie.

7. The system of claim 6 wherein the selected specie is silicon bromide (SiBr).

8. The system of claim 7 wherein the selected band wavelength of the SiBr radiation is given by λ = 407 nm.

9. Method for in-situ and on-line monitoring of a trench formation process in a silicon wafer completed in a dry etching equipment which causes the redeposition of an SiO_2 layer (18) during trench formation characterized in that in real time it comprises the steps of:

generating an interferometric signal Ii as a function of time t of a quasi-periodic damped type which is representative of the SiO_2 redeposited layer reflectivity;

computing the quasi half-period tu of said interferometric signal Ii as soon it is available;

elaborating the envelope signals Ja and Jb of said interferometric signal Ii and signal I = Ja-Jb corresponding to the amplitude variation of said envelope signals;

continuously monitoring the trench formation parameters: trench depth D through $D = k\sqrt{I(t=0)-I}$ wherein k is a coefficient depending on the etching system that is used and is determined by a preliminary calibration step, and the redeposited SiO_2 layer thickness Th through:

$$Th = \left(\frac{\lambda}{4\ n\ tu}\right) \cdot t$$

wherein

λ = Wavelength of the selected band
n = Refractive index of layer 18
tu = Half-period of signal Ii
t = Etch time

10. The method of claim 9 wherein said step of generating said interferometric signal Ii comprises the steps of:

generating a first signal Il as a function of time representative of the band intensity change in the plasma;

generating a second signal It as a function of time t representative of both the band intensity change in the plasma and the reflectivity of the said SiO_2 redeposited layer; and,

substracting said first signal Il from said second signal It to produce said interferometric signal Ii.

11. The method of claim 10 wherein said first signal Il is the current supplied by a first spectrometer viewing the plasma at a zero angle of incidence of the wafer and in a close vicinity thereof, and said second signal It is the current supplied by a second spectrometer viewing the wafer through the plasma at a normal angle of incidence .

12. A method of fabricating a semiconductor device provided with a trench structure including the steps of:

etching a trench into a silicon wafer (24) disposed on a support in an etch- treatment chamber (22) provided with side and top windows (26A, 26B) and connected to a power supply source (25) to generate a plasma (27) within said chamber; and

monitoring said etching step which causes the redeposition of an SiO_2 layer;

characterized in that:

said monitoring step consists of the following substeps:

elaborating a first signal Il as a function of time t representative of the band intensity variation of a selected specie by viewing the plasma in a plane parallel to the plane of the wafer and at the close vicinity thereof;

elaborating a second signal It as a function of time t representative of the said band intensity variation and of the wafer surface reflectivity by viewing the wafer perpendicularly through said plasma;

subtracting said first signal Il from said second signals It, to elaborate a difference signal Ii which basically consists of the interferometric component of said second signal;

elaborating the envelope signals Ja and Jb of said interferometric signal Ii and determining the signal I representative of the amplitude variation of said envelope signals;

continuously monitoring in real time the trench depth $D = k\sqrt{I(t=0) - I(t)}$, wherein k is a coefficient depending on the etching system that is used and is determined by a preliminary calibration step, and

the thickness Th of the said redeposited SiO_2 layer by :

$$Th = \left(\frac{\lambda}{4\ n\ tu}\right) t$$

wherein

- λ = Wavelength of the selected band
- n = Refractive index of layer 18
- tu = Half-period of signal li
- t = Etch time

and,

stopping the etching process at the final time tf when the trench fulfills the desired final values of key parameters: the final trench depth Df and the final thickness Thf.

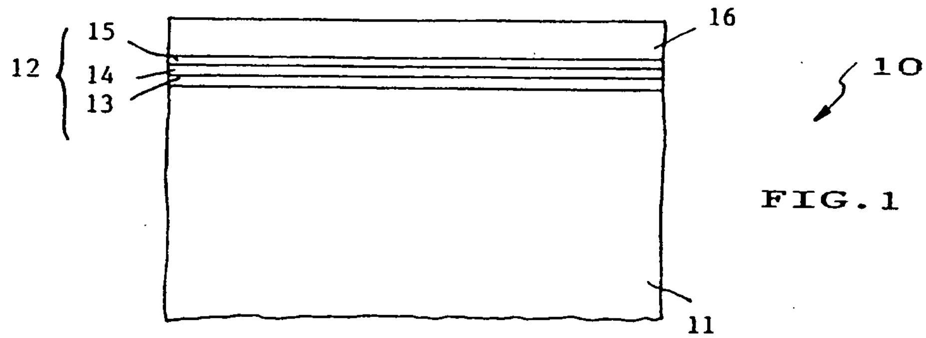

FIG.1

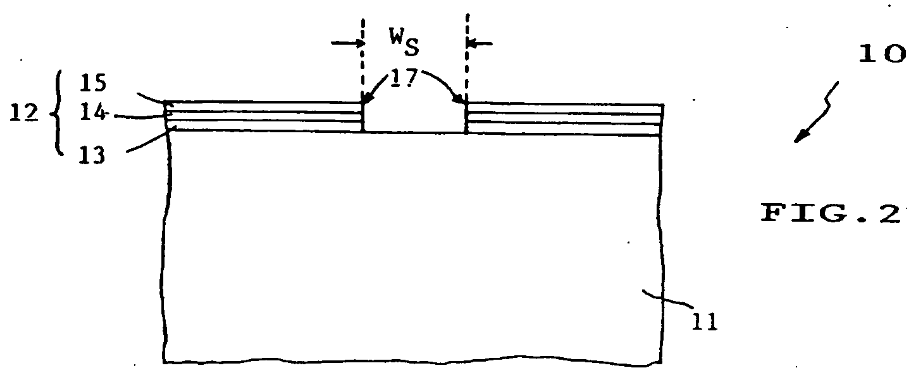

FIG.2

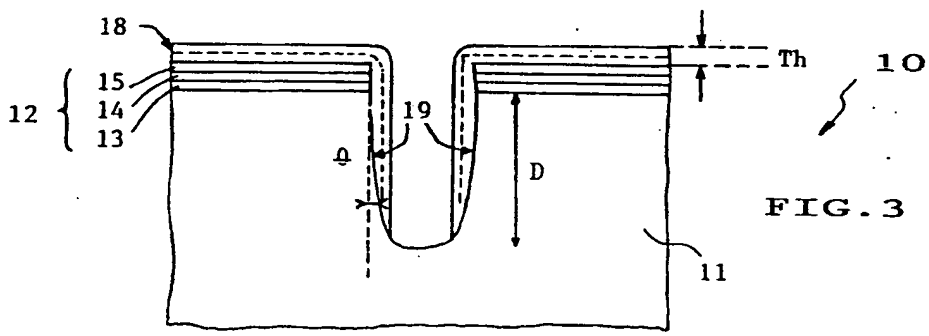

FIG.3

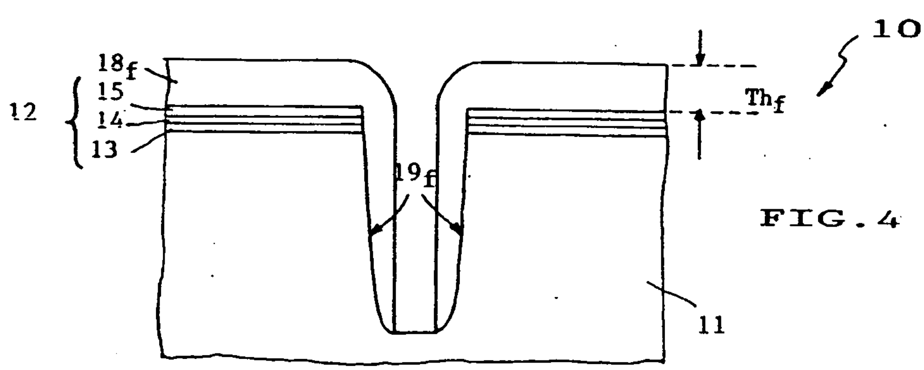

FIG.4

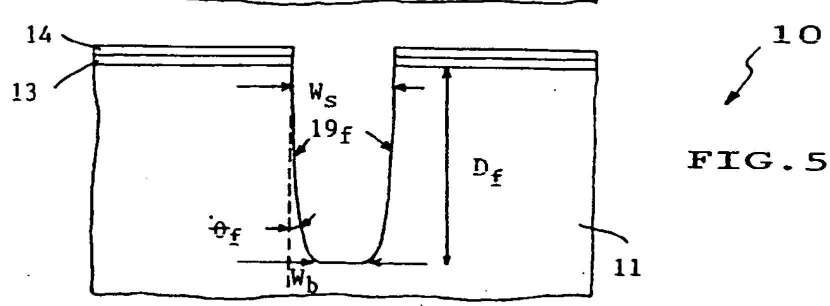

FIG.5

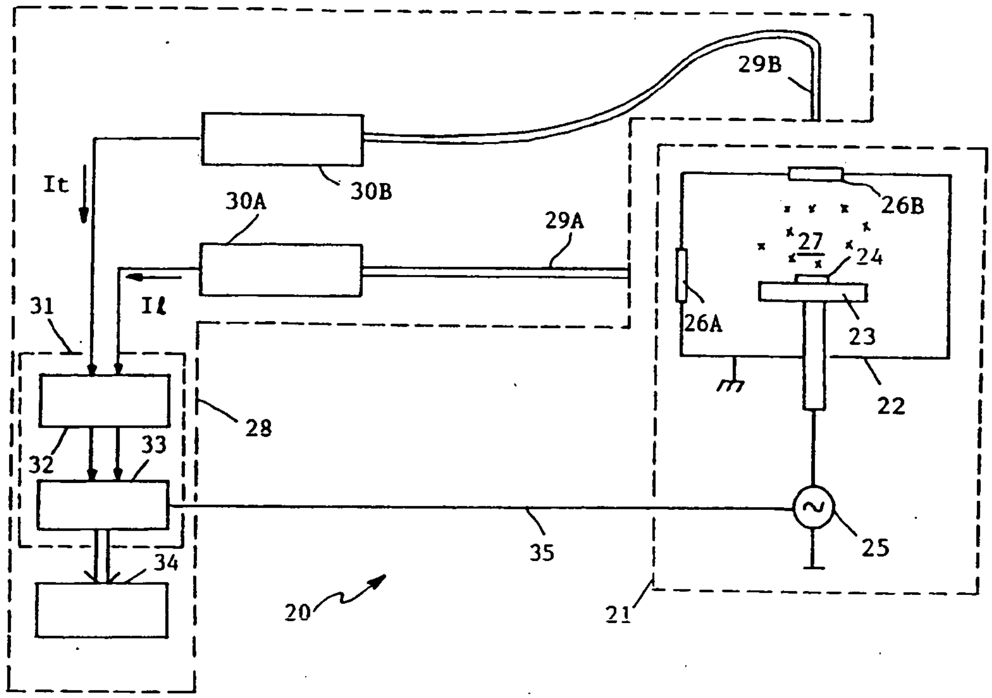

FIG. 6

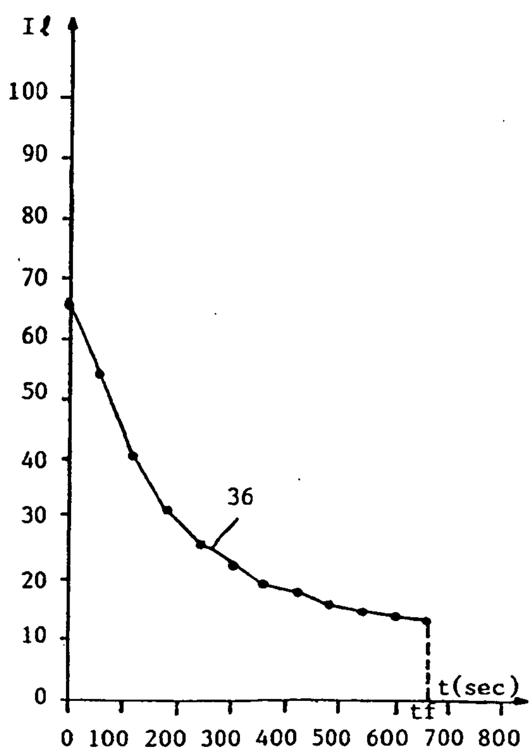

FIG. 7

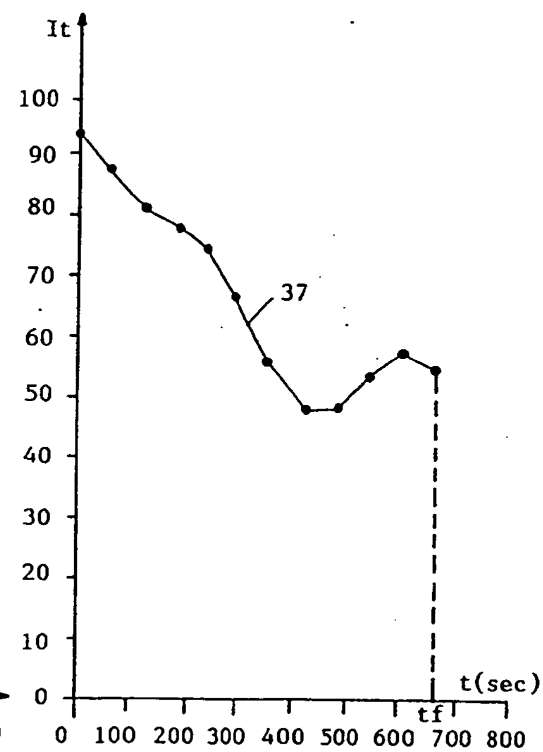

FIG. 8

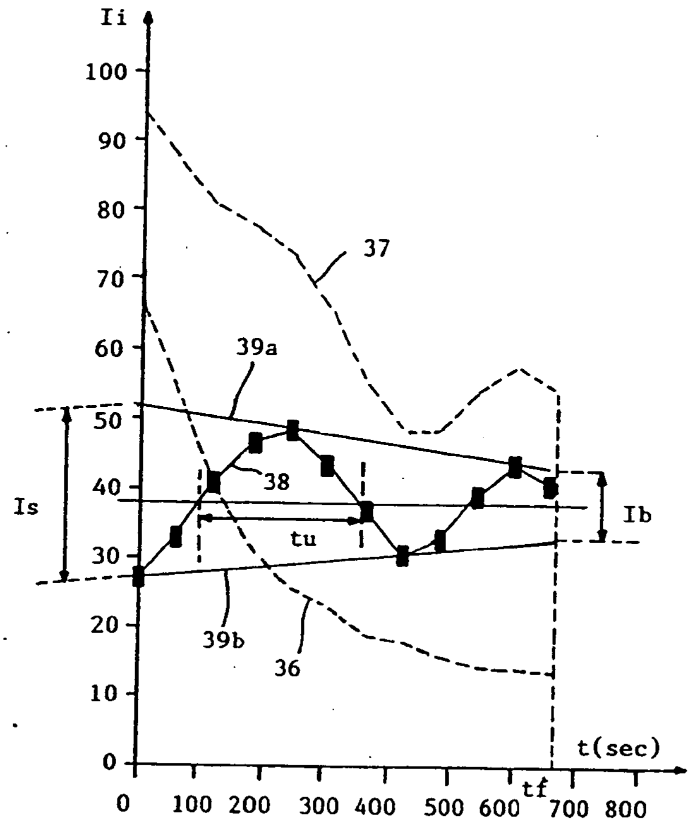

FIG.9

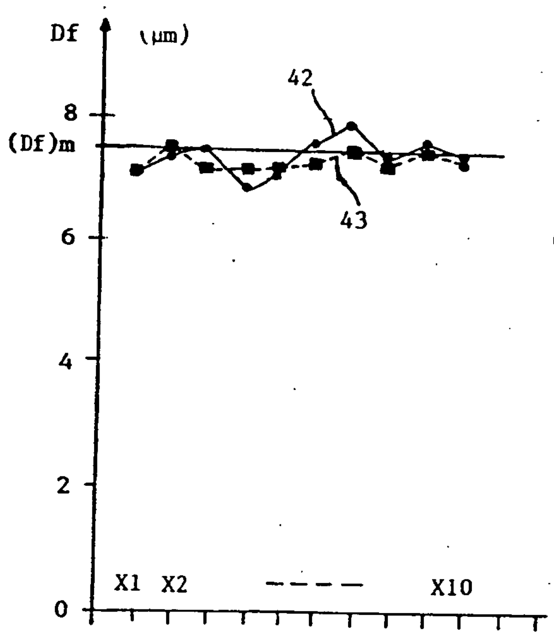

FIG.11

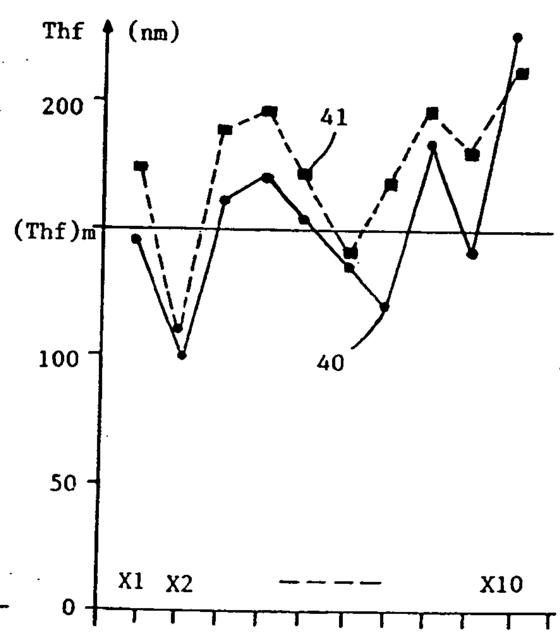

FIG.10

European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP 91 48 0070

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
D,A	EP-A-394597 (IBM) * page 6, line 48 - page 7, line 58; claims 9, 12, 16; figure 4 * ---	1-5, 9, 12	H01L21/306 H01J37/32 G01J3/00
A	US-A-4615761 (KEIJI TADA ET AL.) * column 3, line 1 - column 4, line 68; figure 2 * * column 6, lines 46 - 61; figure 5 * ---	1-4, 9, 12	
A	EXTENDED ABSTRACTS, FALL MEETING, SEATTLE, WASHINGTON 14 October 1990, PRINCETON, NEW JERSEY pages 410 - 411; K.J. COOPER et al.: "Physical and electrical characteristics of submicron trench capacitors" * page 410, left-hand column * ---	9, 12	
A	PATENT ABSTRACTS OF JAPAN vol. 10, no. 117 (E-400) 02 May 1986, & JP-A-60 253228 (HITACHI SEISAKUSHO K.K.) 13 December 1985, * the whole document * ---	1-4	**TECHNICAL FIELDS SEARCHED (Int. Cl.5)**
A	PATENT ABSTRACTS OF JAPAN vol. 8, no. 127 (E-250) 14 June 1984, & JP-A-59 040534 (HITACHI SEISAKUSHO K.K.) 06 March 1984, * the whole document * -----	1, 4, 5	H01J H01L G01N G01B G01J C23F H01H H05H

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
BERLIN	05 DECEMBER 1991	KLOPFENSTEIN P.

CATEGORY OF CITED DOCUMENTS

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